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CRRESRAD Documentation



Kevin J. Kerns, Capt, USAF
M.S. Gussenhoven

6 August 1992

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13. ABSTRACT (Maximum 200 words) <p>This technical report documents the software package CRRESRAD developed by the Phillips Laboratory. CRRESRAD is a utility that predicts satellite dose accumulation behind different thicknesses of aluminum hemispheres for specified orbits. Dose accumulation is predicted by using empirical dose rate models created using data measured on the Combined Release and Radiation Effects Satellite (CRRES) which flew in a geosynchronous transfer orbit for 14 months during solar maximum. The dose models give dose rates for quiet, average, and active conditions during solar maximum which can be used to give best and worst case dose rates. CRRESRAD is best applied to orbits with inclinations less than 30°. It is useful for higher inclination orbits if the user is primarily interested in dose caused by protons or dose accumulated behind thick shielding (> 200 mils aluminum).</p>				
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CRRESRAD Documentation

1. OVERVIEW

CRRESRAD predicts the amount of radiation received in a specified orbit behind four hemispheres of aluminum with thicknesses of 82.5, 232.5, 457.5, and 886.5 mils. The prediction uses empirical models of accumulated dose measured on the Combined Release and Radiation Effects Satellite (CRRES) flown from 25 July 1990 to 12 October 1991 during solar maximum. CRRES was in a geosynchronous transfer orbit with an inclination of 18°, a perigee of 350 km and an apogee of 33000 km. CRRES traversed the radiation belts twice per orbit with a period of 9 hours 52 minutes. The instrument used to measure accumulated dose is the CRRES Space Radiation Dosimeter which measures both dose rate and accumulated dose in four silicon detectors each of which is behind an aluminum dome of different thickness (Hardy *et al.*, 1985, Morel *et al.*, 1989). The minimum energies required for particles to penetrate the domes and accumulate dose in the silicon detectors underneath are 20, 35, 50, and 75 MeV for protons and 1, 2.5, 5, and 10 MeV for electrons. Dose from particles depositing 0.05-1 MeV and 1-10 MeV is accumulated in two different channels called LOLET and HILET respectively. HILET dose accumulates primarily from protons with energies of 20-100 MeV, but electrons with energies >5 MeV may contribute during large electron enhancement periods. LOLET dose accumulates from electrons, bremsstrahlung, and protons with energies >100 MeV. The details of binning the dosimeter data and its use to predict dose rate are presented in Section 2.

Dose measurements on CRRES and the Defense Meteorological Satellite Program (DMSP) show that the current NASA models used to predict dose for satellite design and orbit determination are not always adequate (Gussenhoven *et al.*, 1987, 1991a, 1991b). A major geomagnetic storm occurred in late March 1991 following an intense solar proton event during which a strong shock front hit the magnetosphere. The result of the shock passage was to change the magnetosphere to a more active configuration (Mullen *et al.*, 1991 and Blake *et al.*, 1992). Before the March storm the NASA models for proton dose (HILET) agreed very well with measured dose in the inner zone, but the NASA models for electrons overestimated the measured dose by as much as an order of magnitude and underestimated the >100 MeV proton dose (LOLET) by factors of 3-4 for the CRRES orbit. After the storm a second energetic proton belt and a third

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energetic electron belt were formed in the slot region where there was previously little radiation, and the intensity of the outer zone electrons increased by an order of magnitude. After the March storm, there was better agreement between measured and modeled electron dose for the 1 MeV population, but the model dose for 2-5 MeV electrons was still too high. Also there was now a significant >7 MeV electron population not included in the models at all (Brautigam, 1992). Empirical dose models were created for the period before the storm (quiet model), after the storm (active model), and the entire mission (average model) (Gussenhoven *et al.*, 1992). These different models can be used to give best and worst case dose rates for a given orbit.

CRRESRAD requires a 80286, 80386, or 80486 DOS based computer with a math coprocessor, a color VGA card, and a hard drive. A printer is not needed, but it is useful. The active directory must be the one containing CRRESRAD.EXE and its support files. CRRESRAD is run by typing "CRRESRAD" on the command line, and CRRESRAD will query the user for the name of the orbit to be evaluated. This name will be used for all of the data files subsequently created for this orbit. The data files can be written to another directory by adding the path to the name. For instance, to run an orbit called "Sample" and store the data in "C:\Orbits\", the name would be specified as "C:\Orbits\Sample". No extension can be given in the name. A sample session for determining the dose rate from a polar orbit is shown in Appendix A. An ASCII README file is included with the CRRESRAD software. To read this file enter "TYPE README | MORE" on the command line and press return. This file documents recent updates to the software and has a directory list of the files which have been included with CRRESRAD. As a precaution against viral contamination, make sure that the ".EXE" files are the same size and date as given in the README file.

2. DOSE MODEL

The motion of the high energy ions and electrons that cause dose deposition in satellites in the Earth's magnetosphere is determined almost entirely by the Earth's magnetic field. These particles are trapped by the magnetic field, and are constrained to bounce back and forth between the north and south poles along magnetic field lines. The paths these particles take are referred to as "shells." Because these particles are constrained to move along magnetic field lines, dose resulting from these particles is best ordered by specifying position with magnetic field parameters instead of using spatial coordinates. The magnetic field parameters used for the dose model are the McIlwain L-parameter (McIlwain, 1961) which is referred to hereafter as L shell, and B/B_0 . In a dipole magnetic field the L shell of a given point in space is the equatorial radial distance in Earth radii (R_E) of the field line passing through the given point. The solid lines in Figure 1 show L shells 2, 3, 4, 5, and 6 of a dipole magnetic field centered in the Earth. The Earth's magnetic field has some non-dipole components, and L shell is calculated by determining which dipole field line the actual field line would correspond to if the Earth's magnetic field were relaxed to a dipole field. B/B_0 is the ratio of the magnetic field magnitude at a point in space divided by the minimum magnitude of the magnetic field on the same field line. The field is strongest near the poles and weakest near the equator so that $B/B_0 = 1.0$ is near the equator and $B/B_0 > 1$ is closer to the poles. For a dipole

field B/B_0 is a function only of magnetic latitude. The dotted lines in Figure 1 show constant B/B_0 contours and their magnitude spaced every 10° in a dipole field from $\pm 40^\circ$ latitude. Chapter 5 of the *Handbook of Geophysics and the Space Environment* (Spjeldvik and Rothwell, 1985) contains a more complete description of the Earth's magnetosphere and the radiation belts.

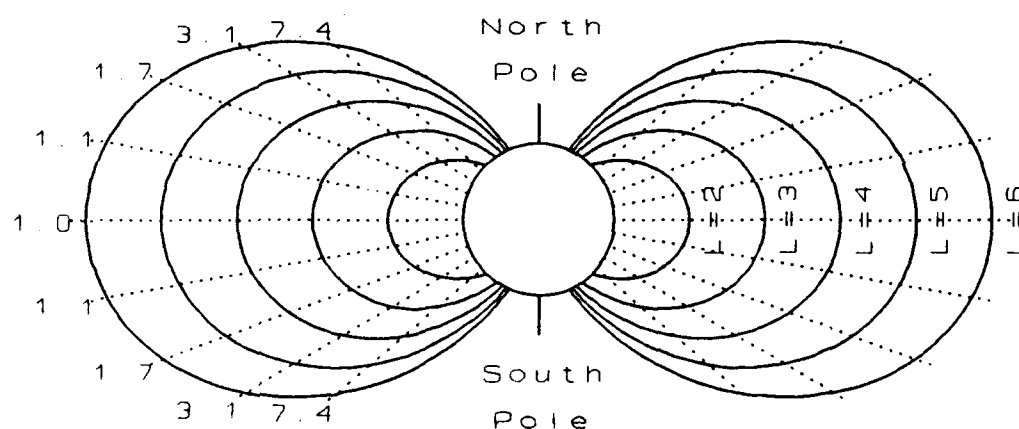


Figure 1. L Shells 2, 3, 4, 5, and 6 (solid lines) and lines of constant $B/B_0 = 1.0, 1.1, 1.7, 3.1,$ and 7.4 (dashed lines) in a dipole field centered in the Earth.

The Olson-Pfitzer static external magnetic field model and the IGRF85 internal magnetic field model were used to calculate the L Shell and B/B_0 values when binning the CRRES dose rate data. The IGRF 85 model specifies the magnetic field that comes from currents internal to the Earth (IAGA Division I, Working Group 1, 1986). This field is nearly dipolar with an 11.5° tilt and 436 km offset with respect to the Earth's spin axis, and it is slowly changing with time (Knecht and Shuman, 1985). The IGRF model accounts for the slow time variation of the field as well as the tilt and non-dipole contributions to the field. The Olson-Pfitzer static model (Olson and Pfitzer, 1974) predicts the changes in the magnetic field caused by currents in the magnetopause, the ring current and the magnetosphere's tail. The model also accounts for the tilt of the Earth's dipole with respect to the Earth-Sun line. The external currents that contribute to the magnetic field change with variations in the solar wind and magnetospheric activity. The static model assumes these currents do not change and uses values from average quiet conditions. We should note that the Olson-Pfitzer external field makes no contribution within an L of $2.4 R_E$.

The dose models used by CRRESRAD are based on in situ dose rate measurements made by CRRES. The instrument used to measure dose is the CRRES Space Radiation Dosimeter described in Section 1. The dosimeter measured accumulated dose once every 4.096 seconds throughout the CRRES mission. The measured dose rates for each dome were binned by L shell and B/B_0 to make average dose rate models in rads (Si) per second. The width of each bin in L shell is $1/20 R_E$, and the width of each bin in B/B_0 is $\sim 2^\circ$ latitude in a dipole field. The bins form a two dimensional array of 140 (L shell) by 20 (B/B_0) and cover L shells of 1 to $8 R_E$ and magnetic latitudes of 0° to

~40°. The CRRES mission is divided into two parts. The magnetosphere is assumed to be in a quiet configuration before the March 1991 storm and in an active configuration after the March storm (Mullen *et al.*, 1991, Blake *et al.*, 1992, and Gussenhoven *et al.*, 1992). A model was made separately for LOLET, HILET, and LOLET + HILET for each of the four domes. Three sets of these models were made: one for quiet conditions before the storm (27 July 1990 to 19 March 1991), one for active conditions after the storm (31 March 1991 to 12 October 1991) and one for average conditions over the entire mission (27 July 1991 to 12 October 1991). These combinations result in 36 different dose rate models, which are stored in the binary files "DOSE_MOD.00" to "DOSE_MOD.35." Appendix B contains a detailed description of these files. There are some statistical differences between the models. Data exists in bins where CRRES was actually located, and the location of CRRES in B and L space was slightly different for the quiet and active periods. The difference occurs in the bins at the limits of CRRES coverage. This uncertainty is generally very small, being less than 10 percent. However, for orbits lying primarily beneath the radiation belts, such as Shuttle orbits, the sampling difference is important. Orbits with apogees near geosynchronous altitudes may show a higher dose rate using the average models than using the active or quiet models because the average model is the only model to use the period between 19 March 1991 and 31 March 1991 during which a strong solar proton event occurred.

3. LOGICAL FLOW OF CRRESRAD

Figure 2 shows a flow diagram of the CRRESRAD execution. The solid arrows indicate the direction of logical flow, and the dashed arrows indicate the input and output required at each step. Between each logical step, CRRESRAD stops and presents the user with information about what it will be doing next, after which it waits for a key to be pressed before continuing. The first step is to input the name of the orbit from the user. This name will be used with all the files generated by CRRESRAD. No extension can be given with the name, but a path may be specified with the name if the files are to be written to some other directory. In Figure 2, the name input is represented as "?NAME?". First time users of CRRESRAD should type "CRRESRAD" on the command line. CRRESRAD will query the user for the name when it runs. A second option for users familiar with CRRESRAD is to include the name on the command line by typing "CRRESRAD ?NAME?". When this option is used, CRRESRAD does not stop to tell the user what it is doing or wait for user input. This allows long runs taking many hours to be done without requiring the user to periodically respond to the CRRESRAD prompts. In this mode, any intermediate files that exist with the given name will automatically be used.

CRRESRAD inputs the orbital elements from the user. These elements describe the orbit to be tested. Only orbits for times after day 1, 1985 can be used. There are three options for specifying orbital elements:

Position and Velocity: The elements for position, r_x , r_y , r_z , and velocity, v_x , v_y , v_z , are specified in km and km/sec using the Earth Centered Inertial (ECI) coordinate system. Time is given in year, day of year,

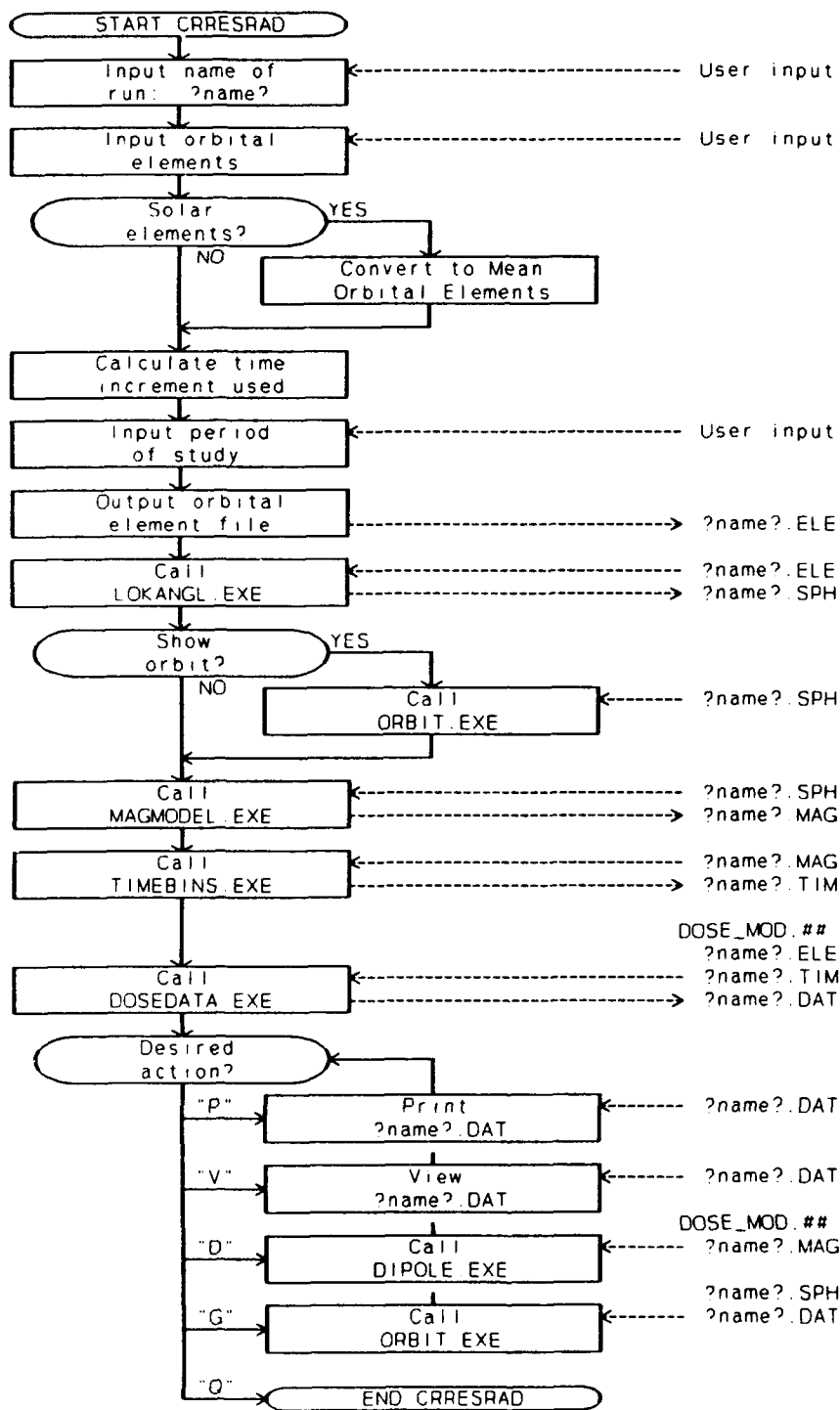


Figure 2. Simplified flow diagram of CRRESRAD. Solid arrows refer to logical flow, and dashed arrows refer to input and output at each step.

hours, minutes and seconds and must be later than the start of day 1, 1985.

Mean Orbital Elements: Inclination, right ascension of the ascending node, argument of perigee, and mean anomaly are specified in degrees, mean motion is specified in revolutions per day, and eccentricity is specified. The format of the given time is as specified for the position and velocity elements.

Solar Elements: Inclination is specified in degrees, while altitudes of apogee and perigee are specified in km assuming $R_E = 6378$ km, and local times of apogee and maximum inclination are specified in hours. These elements are useful to scientists and engineers concerned with where an orbit is with respect to the sun and to those who are not familiar with the standard orbital elements. The solar elements are not a full set of elements because there are only five elements (besides time) to input. The sixth element results from the assumption that the orbit is at apogee at the time for which the elements are specified. A local time of apogee of 12.0 indicates that the satellite is at apogee directly between the sun and the Earth. Local time of maximum inclination indicates the local time where the geographic latitude of the satellite is at a maximum positive value. Default values of 12.0 and 18.0 are used respectively for the two local times, but these values may be changed. A six hour difference between the local time of apogee and the local time of maximum inclination causes apogee to be at 0° geographic latitude. In many cases this difference results in the greatest amount of radiation because the highest dose rates occur near the magnetic equator which is close to the geographic equator. There are many cases where the six hour difference does not result in the greatest dose accumulation. One case is an elliptical polar orbit having an apogee with the same radius as the equatorial slot region. The format of the given time is as specified for the position and velocity elements. The solar elements cannot be used by LOKANGL.EXE directly, so CRRESRAD converts these elements into mean orbital elements (see Appendix C).

The elements are checked to make sure that the orbit is not hyperbolic and that perigee is not below the surface of the Earth (see Appendix C). The time step used in the study is chosen so that the orbit will sweep $\sim 2^\circ$ arc at perigee in a single time step (see Appendix C). CRRESRAD then inputs the start time (which must be after day 1 1985) and length of the study from the user. The elements are written to an ASCII file called ?NAME?.ELE.

CRRESRAD calls LOKANGL.EXE which reads the element file and generates an ephemeris file, ?NAME?.SPH, which contains geographic position. The position is calculated at each time increment in the specified period of study. Appendix D contains a description of the ?NAME?.SPH file. LOKANGL.EXE is used at the Phillips Laboratory Geophysics Directorate to predict positions of Earth satellites using orbital elements as an input. The code was recently modified by RADEX Inc. for use on the

IBM PC. Contact this office (PL\GPSP) for information on the format of the ?NAME?.ELE file as well as a detailed description of LOKANGL.EXE. LOKANGL.EXE calculates the position of an Earth satellite using a perturbation expansion with the second and third zonal harmonics of the Earth's gravitational field. It is not considered accurate for times more than one hundred days from a specified orbital element. After a set of elements has been entered, CRRESRAD waits for the user to press "D" to indicate that the elements are done. The user can press "E" instead of "D" to enter another set of elements for the same orbit. "D" is pressed after the last set of elements is entered. If multiple elements are specified, LOKANGL.EXE will interpolate between these elements to improve accuracy. LOKANGL.EXE cannot evaluate hyperbolic or parabolic orbits or orbits where the radius becomes less than one Earth radius. When LOKANGL.EXE is done, CRRESRAD will give the user the option to view the orbit by calling ORBIT.EXE. Appendix E contains a description of ORBIT.EXE. If the file name was given on the command line, CRRESRAD will not give the option to view the orbit and will proceed on to the next step.

CRRESRAD calls MAGMODEL.EXE (see Appendix E) to convert the geographic coordinates in ?NAME?.SPH into magnetospheric coordinates that are put into the binary file ?NAME?.MAG. The routines used by MAGMODEL.EXE to calculate L shell and B/B₀ were developed by Karl Pfizter at McDonnell Douglas Space Systems Corp for the Air Force (Pfizter, 1991). The IGRF 85 model used by MAGMODEL.EXE is only valid for times after the start of day 1, 1985. The magnetospheric ephemeris file is read by TIMEBINS.EXE, which is called next by CRRESRAD. This utility reads the ephemeris data and interpolates between points using a cubic spline to determine how much time the orbit spends in each of the bins defined for the dose models. The resulting array is written to the binary file ?NAME?.TIM. CRRESRAD then calls DOSEDATA.EXE. This utility reads in the times in each bin from ?NAME?.TIM, and multiplies these times by the dose per bin read from the DOSE_MOD.## files. The total dose received in the orbit is the sum of the products of each of the bins. The integration is performed once for each DOSE_MOD.## file found. DOSEDATA assumes that the first 36 files (## = 00-35) are the standard dose files, and these files should not be renamed. Any other DOSE_MOD.## files found in the active directory will also be integrated and included in the output. The integrated data is output to a formatted ASCII file called ?NAME?.DAT. Appendix F shows the contents of SAMPLE.DAT which was generated in Appendix A. The top section gives the name, orbital elements, and the times of the study. After the time of study, the amount of the orbit (by time) not covered by the dose bins is given. A polar orbit is used in SAMPLE.DAT, but the bins only cover $\sim \pm 40^\circ$ latitude. As a result, 57.9 percent of the orbit (by time) was outside of the bin ranges. The next section is a table showing dose converted to rads (Si) per year. The table uses the first 36 DOSE_MOD files and shows different doses for different activities and combinations of HILET and LOLET. The final section is a data table that provides the specifications of the four domes used. Integration results from other DOSE_MOD files are included before the Dosimeter data table.

At this point CRRESRAD is done with calculations and provides several options to view the data. Pressing "P" calls the DOS command "COPY ?NAME?.DAT PRN," which will print the ASCII file ?NAME?.DAT. Pressing "V" displays the file on the

screen. "G" graphs the orbit using ORBIT.EXE. "D" graphs the orbit superimposed on the dose models using DIPOLE.EXE (see Appendix E), and "Q" quits CRRESRAD. A benchmark file is created by CRRESRAD which shows how long each of the different utilities took to run. This file has the name ?NAME?.BEN and is discussed in more detail in Appendix A.

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Appendix A

Sample Session

Enter the CRRESRAD subdirectory by typing:

cd \crresrad <Enter>

Then type:

CRRESRAD <Enter>

Press any key once you have read the information on the screen. You are now asked for a file name. Here we use "Sample" as the file name. Type:

Sample <Enter>

Press any key once you have read the information on the screen. Press "S" to select solar elements. On the next screen we specify an orbit that is very similar to the orbits used by the Defense Meteorological Satellite Program satellites. Enter the solar elements and the time for which those elements apply:

year	1993
day	179
hour	12
minute	0
second	0
Inclination	98
Perigee	840
Apogee	840

Leave the two default local times as they are at 12 and 18. We assume the elements apply at 12 UT on 28 June 1993. If the orbit was not circular, the satellite would be at apogee at that time. If you enter something incorrectly, you can tab back to that line and enter it again. Pressing "x" then <Enter> on a line will delete it. When you are done press "D." If we wanted to specify multiple elements, we would press "E" instead of "D," and CRRESRAD would ask for another set of elements. At the next screen enter the time of the study:

year	1993
day	179
hour	6
minute	0
second	0
length	0.5 (days)

The time of the study can differ from the time entered previously for the element information. Press "D" when you are done.

A message will appear on the screen estimating the calculation time for a 25 Mhz 80386 computer. In this case the orbit dose will take about 4.9 minutes to calculate. The actual time required will vary with the speed of the computer and the type of orbit. In general, lower altitudes take longer than higher altitudes, elliptical orbits take longer than circular, and high inclination orbits take longer than low inclination. If you wish to terminate the program at this point press "N;" otherwise press "Y" to continue, and then press any key once you have read the information on the screen.

The code LOKANGL.EXE will execute. In the upper left corner of the screen is written "00004.9" which is the estimated time to completion in minutes. Below it is written the actual execution time. Once LOKANGL.EXE is done executing, CRRESRAD will ask if you would like to see the orbit. Press "Y" to execute ORBIT.EXE which shows a view of the orbit. The view in the lower right looks down on the Earth's North pole with the sun towards the top. The other two images show side views, looking along X and Y. The orientation of the axes on these views follows standard drafting conventions. Press "Q" to quit ORBIT.EXE, then press any key once you read the information on the CRRESRAD screen.

The code MAGMODEL.EXE will execute. The actual execution time (upper left corner of screen) does not start from zero, but begins where it left off when LOKANGL.EXE was executing. MAGMODEL.EXE takes the most time of the utilities used. When it is done, press any key after reading the information on the screen.

The code TIMEBINS.EXE will execute. This code runs faster than LOKANGL.EXE and MAGMODEL.EXE. When it is done, press any key after reading the information on the screen.

The code DOSEDATA.EXE will execute. The time taken by this code does not depend on the size of the run. When it is done, press any key after reading the information on the screen.

You now have several options for viewing the data. If you have a printer, press "P" to get a printout. You can also press "V" to see the output on the screen ("Q" will return you to the menu). Appendix F is a copy of the printout of the file SAMPLE.DAT. Pressing "G" calls ORBIT.EXE to show the orbit plot again. Notice that more information is displayed in the upper left corner now that the job is complete. This information comes from the header in SAMPLE.DAT. "D" executes DIPOLE.EXE which shows the orbit track through the radiation belts. The orbit track is plotted entirely in the upper quadrant. Although this may at first seem unnecessarily confusing, it does allow one to use the lower quadrant to view the radiation belt intensities without orbit track obstruction. Notice that for "Sample" the orbit is below the most intense part of the radiation belts. This utility shows that CRRESRAD may underestimate the dose because a good portion of the orbit passes through the edge of the outer radiation belt at high latitudes where it was not measured by the Dosimeter. The underestimation is also indicated on the printout which states that 57.9 percent (by time) of the orbit was not covered by the valid range of CRRESRAD. The dose estimate is good for HILET data behind all four domes and for LOLET data behind domes 3 and 4 (Gussenhoven *et al.*, 1992).

The time required for your computer to predict the orbit for Sample is recorded in the ASCII benchmark file called SAMPLE.BEN. On the next page is a copy of the benchmark file for Sample used on a 25 Mhz 386 COMPUADD computer at the Phillips Laboratory.

```
***** Time increment = 33.91 seconds.
08:18:15.17 --> LOKANGL started
08:18:47.36 --> LOKANGL finished
Number of points = 1277
08:19:47.45 --> MAGMODEL started
08:23:52.14 --> MAGMODEL finished
08:30:37.11 --> TIMEBINS started
08:30:43.86 --> TIMEBINS finished
08:30:50.12 --> DOSEDATA started
08:30:54.96 --> DOSEDATA finished
```

Time increment is the step size chosen by CRRESRAD to calculate ephemeris and dose. This time was chosen so that the satellite swings through approximately 2° arc at perigee (Appendix C). LOKANGL took 32.19 seconds to run, MAGMODEL took 244.69 seconds, TIMEBINS took 6.75 seconds, and DOSEDATA took 4.84 seconds. The rest of the time was spent waiting for user input and was not considered in the estimated run time of 4.9 minutes. The actual time taken was 4.8 minutes while the estimate was for 4.9 minutes. The estimate tends to be a worst case estimate. By comparing your benchmark file to the one shown above you can calculate the speed of your computer versus the benchmark computer. This ratio applies to the estimated run time.

Appendix B

Format of DOSE_MOD.## Files

The DOSE_MOD.## files contain data binned by L Shell and B/B₀. Any rate data such as dose rate or flux can be put into these files, provided the following format is used:

- The filename must be DOSE_MOD.## (## = 00 to 99)
- The file structure is of the type:

-- TURBO PASCAL

```
Type
DoseRecord = record
    MainTitle,
    SubTitle,
    Units      : String[79];
    d          : Array[1..140,1..20] of Single;
end;
```

-- ANY OTHER LANGUAGE

```
MainTitle,
SubTitle,
Units      : Each is an array of 80 eight bit bytes or characters. The
              first byte contains the number of characters in the array (0
              to 79). The following bytes contain the characters in the
              array.
d          : This is the data. Each bin is a 4 byte real number follow-
              ing the convention set by the Intel math coprocessor. The
              data is binned in a two dimensional array of 1 to 140 (L
              shell) by 1 to 20 (B/B0). Consecutive B/B0 bins occupy
              consecutive spaces in memory.
```

- The files have four different groups of information.

-- The first three groups are strings. **MainTitle** and **SubTitle** are strings of characters that are displayed as the two title lines by the utility **DIPOLE.EXE**. **Units** is the string displayed by **DIPOLE.EXE** near the scale, and it identifies what type of data is displayed. **CRRESRAD** integrates the data in **DOSE_MOD** files by time. As a result, **Units** in **DOSE_MOD** files used by **CRRESRAD** must be rate data, but "per second" must be replaced by "&." When **DIPOLE.EXE** sees the "&," it replaces it with "per second" when displaying the data.

-- The final group is the data bins. **d** is a two dimensional array containing 1 to 140 (L Shell) by 1 to 20 (**B/B₀**) bins.

--- **i** is the index associated with L Shell, and **i** ranges from 1 to 140. The limits of bins with index **i** are: $0.95 + 0.05i R_E \leq \text{L Shell} < 1.00 + 0.05i R_E$

--- **j** is the index associated with **B/B₀**, and **j** ranges from 1 to 20. The limits of bins with index **j** are:

$B_{j-1} \leq B/B_0 < B_j$
 $B_{0...20} = 1.000, 1.004, 1.020, 1.046, 1.085, 1.140, 1.200, 1.300,$
 $1.400, 1.520, 1.690, 1.880, 2.100, 2.400, 2.730, 3.130, 3.670,$
 $4.350, 5.020, 6.100, 7.410.$

--- The values of **B_j** are such that the limits **B₀** to **B₂₀** cover approximately $\pm 40^\circ$ magnetic latitude in a dipole field.

Appendix C

Calculations Used to Create Element File

We give here the equations used (1) to calculate the time step used in LOKANGL.EXE; (2) to convert solar elements to mean orbital elements; and (3) to eliminate invalid orbits, namely those that are not closed or that pass close to or beneath the surface of the Earth. Two constants specific to Earth that are used throughout are μ , the gravitational constant times the mass of the Earth, and R_E the radius of the Earth assuming the Earth is spherical. These values are:

$$\begin{aligned}\mu &= 398601.2 \text{ km}^3\text{sec}^{-2}, \\ R_E &= 6378.145 \text{ km}.\end{aligned}$$

(1) Time Step Calculation:

If Position/Velocity Elements are used where

$$r = \sqrt{r_x^2 + r_y^2 + r_z^2}, \quad v = \sqrt{v_x^2 + v_y^2 + v_z^2}$$

define the three quantities, a , h , and e as

$$a^{-1} = \frac{2}{r} - \frac{v^2}{\mu}, \quad h = |\vec{r} \times \vec{v}|, \quad e^2 = 1 - \frac{h^2}{\mu a}.$$

Here a is the semimajor axis in km, h is the angular momentum in km^2/sec , and e is the eccentricity.

If Mean Orbital Elements are used, the eccentricity e and the mean motion M_m in revolutions per day are given as elements. The semimajor axis a and the magnitude of the angular momentum h are given by:

$$a^3 = \mu[(12 \cdot 3600)/(\pi M_m)]^2, \quad h^2 = \mu a(1 - e^2)$$

In terms of a , h , and e , the time step T_s , which is approximately equal to the time to traverse 2° arc at perigee is:

$$T_s = a^2(1 - e^2)h^{-1} \frac{\pi}{90}$$

In this calculation $d\theta/dt$ at perigee is assumed to be constant over the 2° arc.

(2) To Convert Solar Elements to Mean Elements:

Use the convention day = 1 on 1 January 1992.

Define the following quantities:

$$r_a = A_a + R_E;$$

$$r_p = A_p + R_E; \quad A_a \text{ and } A_p \text{ are altitudes from the surface of the Earth in km;}$$

$$H_o = 6.594703 + 0.0657098243 \cdot \text{day} + 1.00273791 \cdot \text{Hr} \quad [\text{U.S. Naval Observatory, 1992}];$$

$$\Theta_a = (H_o + 12) \cdot \pi / 12, \text{ where } H_o \text{ is local time of apogee;}$$

$$\Theta_i = (H_i - 6) \cdot \pi / 12, \text{ where } H_i \text{ is local time of maximum inclination.}$$

Then the six elements are:

inclination, i , is given;

$$\text{eccentricity, } e = (r_a - r_p) / (r_a + r_p);$$

mean anomaly, $M = 180^\circ$ (satellite is at apogee when elements are defined);

$$\text{squared mean motion, } n^2 = \mu / [1/2(r_a + r_p)]^3 (12 \cdot 3600 / \pi)^2;$$

$$\text{right angle of ascending node, } \Omega = 15(H_i - 6 + H_o);$$

$$\text{argument of perigee, } \omega, \cos(\omega) = \cos(\Theta_a)\cos(\Theta_i) + \sin(\Theta_a)\sin(\Theta_i).$$

(3) Check Elements for valid orbit:

The orbit is valid if:

$$\text{a) the orbit is closed: } 0 \leq e^2 < 1;$$

$$\text{b) perigee is not below the surface of the Earth: } a(1 - e) \geq 6400 \text{ km.}$$

Appendix D

Format of Ephemeris Files

The geographic ephemeris files end with the extension "SPH." These are binary files that are output from LOKANGL.EXE. Each record of the file specifies the position of a satellite, and the time interval between all records is constant (T_s is in Appendix C). These files are input by MAGMODEL.EXE to produce the magnetospheric ephemerides.

Each record of the file contains, in the following order:

year	: 2 byte integer
day	: 2 byte integer
second	: 4 byte real
latitude	: 4 byte real (deg)
longitude	: 4 byte real (deg)
radius	: 4 byte real (km)

The magnetospheric ephemeris files end with the extension "MAG." These are binary files that are output from MAGMODEL.EXE. Each record of the file specifies the position of a satellite in the Earth's magnetic field, and the time interval between all records is constant (T_s). The requirement for a constant time step is set by TIMEBINS.EXE. These files are input by TIMEBINS.EXE to produce files indicating how much time the orbits spend in the magnetospheric bins defined for the dose models (see Appendix B).

Each record of a file contains, in the following order:

L Shell	: 4 byte real (R_E)
B/B ₀	: 4 byte real

Open field lines are indicated by an L shell of -1 or L shells $> 15 R_E$.

The last record of each file contains, in the following order:

-100	: 4 byte real
TimeStep	: 4 byte real (time interval between steps)

LOKANGL.EXE can be bypassed by creating a ".SPH" ephemeris file of the proper format. CRRESRAD will still request orbital elements so you must generate a dummy element file, but CRRESRAD will not execute LOKANGL.EXE if the ".SPH" file exists. In the same way, a different magnetospheric model can be used by creating a ".MAG" file of the proper format. CRRESRAD will still request orbital elements, and will run LOKANGL.EXE (if a ".SPH" file does not exist), but it will not execute MAG-MODEL.EXE.

Appendix E

CRRESRAD Support Programs

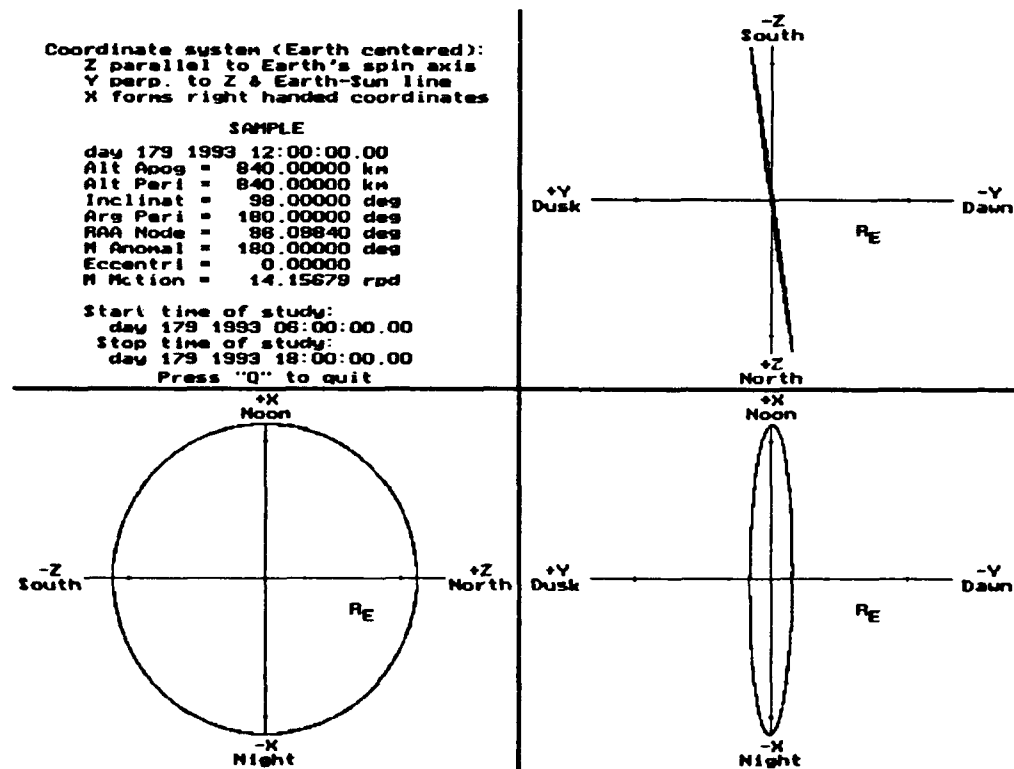


Figure E1. ORBIT.EXE screen.

ORBIT.EXE - This is a display utility program that works on a color EGA/VGA monitor. It is called by CRRESRAD, but may also be called from the command line. This program reads the ".SPH" files, and will also read the ".DAT" files if they exist. When calling ORBIT.EXE from the command line, the name of the run must be included

on the command line. The name of these files may include a path, but not an extension. If one typed "ORBIT \ORB\SAMPLE," the data file SAMPLE.SPH in the directory "\ORB" would be displayed. If SAMPLE.DAT exists then orbital elements read from that file would be displayed in the upper left corner. Figure E1 shows a screen capture of ORBIT.EXE using the files created in the sample session of Appendix A. The upper left corner shows information about the orbit drawn. In the coordinate system used (see Figure E2), Z points along the Earth's spin axis and is positive toward the north pole, while Y is perpendicular to Z and the Earth-Sun line and is positive towards dusk. X completes the right handed coordinate system and goes through the noon meridian. The lower right corner of Figure E1 shows the orbit projected into the XY plane. Tick marks show integer numbers of R_E . The other two corners show the orbit projected into the XZ, and YZ planes. The orientation of the coordinates follows drafting convention where the figure in the lower right corner is the top view and the other two figures are side views. Pressing "Q" exits the program.

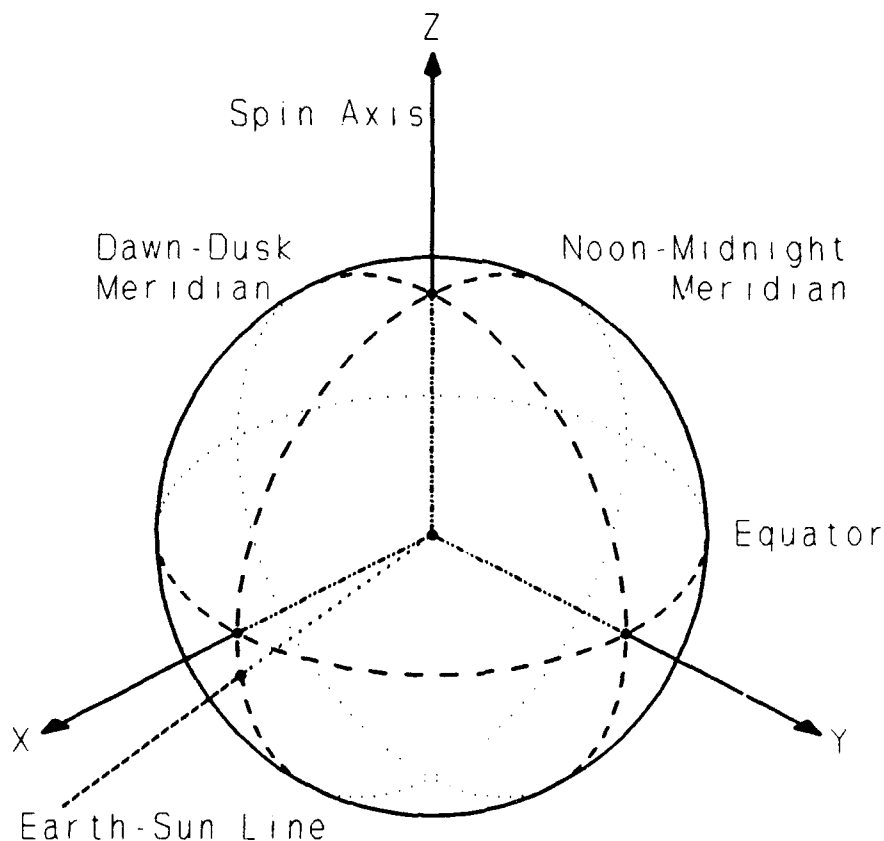


Figure E2. Coordinate system used for ORBIT.EXE.

MAGMODEL.EXE - This program uses the IGRF 85 and Olson-Pfitzer Static Magnetic Field Model IBM PC Fortran routines developed by Karl Pfitzer (1991). To use this code two command line parameters are required. The first is the path of the source file (including name and extension), and the second is the path of the destination file

(including name and extension). The source file is a geographic ephemeris file, and the destination file is a magnetospheric ephemeris file. The formats of both these files are described in Appendix D.

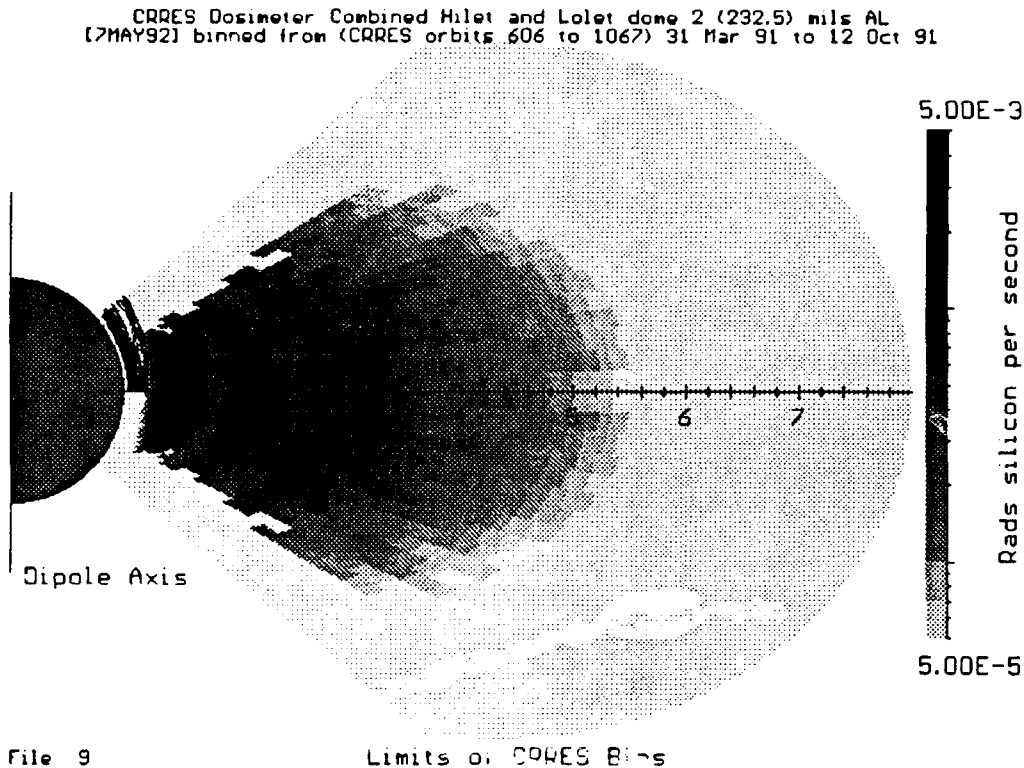


Figure E3. DIPOLE.EXE screen displaying SAMPLE.MAG orbit.

DIPOLE.EXE - This program displays the dose rate data in the DOSE_MOD.## files. The data is placed spatially on the screen as it would look if the Earth's magnetic field were a dipole (the image will not be proportioned correctly if an EGA card is used). Figure E3 shows a copy of the screen when DIPOLE.EXE is displaying the orbit generated in Appendix A. The figure is shown in gray scale, but the program is displayed in color. Colors on the screen will be bracketed. The [cyan] half circle on the left side of the screen represents the Earth with the magnetic axis pointing straight up. Gray scales [color codes] represent dose rate intensity. Higher dose rates tend towards the darker shading [reds], and lower dose rates tend towards the lighter shading [blues]. If the dose rate is above the color scale, it will be shown as black [white], and if the dose rate is below the color scale or there is no data, it will be shown as dark [light] gray. Pressing the space bar shows an options menu. The color scale can be reset and can be changed from a log to a linear scale. One can move to a higher (lower) dose model by pressing the plus (minus) key. Pressing "Q" quits the program. The orbit in L shell versus B/B_0 is plotted as a black line on the upper quadrant of the dose rate data. The orbit is plotted in only one quadrant because B/B_0 contains no information about +/- latitude. This causes the orbit to be folded into the upper quadrant. In Figure E3 the

orbit is below $1.2 R_E$ and shows up as a dark band just below the lower edge of the inner belt in the upper quadrant. The dose model in Figure E3 shows dose rate behind dome 2 for HILET + LOLET during the post March storm period. Three belts with peaks at 1.2, 2.2 and $3.0 R_E$ show up clearly in the figure.

The orbit plot superimposed on the dose rate data can be used to analyze the effectiveness of CRRESRAD for the given orbit. Portions of low orbits may actually be drawn below the surface of the Earth on the plots. This results from the fact that the Earth is not actually spherical, the magnetic field is not actually dipolar, and the center of the magnetic field is not at the center of the Earth. The valid range of the CRRES data can be seen clearly from looking at the dose rate plots. Regions with a significant amount of dose may be missing at high latitudes from LOLET domes 1, 2 dose. This missing data may cause the dose rate for orbits with high inclinations to be underestimated.

DIPOLE.EXE can be run from the command line by typing "DIPOLE." Dipole will ask for the file number to be displayed, and will then graph the data. The file number can also be specified on the command line. To show DOSE_MOD.09 one would type "DIPOLE 9." A second command line parameter can be included to show an orbit superimposed on the dose rate map. The second parameter must be the path (including name and extension) of a magnetospheric ephemeris file. The file must be of the format given in Appendix D.

Appendix F

Contents of SAMPLE.DAT

CRRESRAD Prediction Utility - SAMPLE

Element time: day 179 1993 12:00:00.00
 Alt Apog = 840.00000 km Alt Peri = 840.00000 km
 Inclinat = 98.00000 deg Arg Peri = 180.00000 deg
 RAA Node = 96.09840 deg M Anomal = 180.00000 deg
 Eccentri = 0.00000 M Motion = 14.15679 rpd

Start time of study: day 179 1993 06:00:00.00
 Stop time of study: day 179 1993 18:00:00.00
 Time of study is 0.49996 days (57.9% of orbit out of range)

Average Yearly Dose Predicted from orbit:

Dome	1	2	3	4
Lolet + Hilet (rads silicon/year)				
Average Activity	565.5	379.2	341.5	243.4
Low Activity	559.9	382.5	343.8	241.1
High Activity	472.5	339.1	313.4	231.3
Hilet (rads silicon/year)				
Average Activity	361.4	252.3	219.4	149.2
Low Activity	360.9	256.6	223.1	151.6
High Activity	280.3	219.2	196.2	135.8
Lolet (rads silicon/year)				
Average Activity	204.1	126.8	122.1	94.2
Low Activity	199.0	125.9	120.6	89.4
High Activity	192.2	119.9	117.3	95.5

Average Activity 27 Jul 90 to 12 Oct 91
 Low Activity 27 Jul 90 to 19 Mar 91
 High Activity 31 Mar 91 to 12 Oct 91

Space Radiation Dosimeter Characteristics

Dome Number	Dome Thickness (mils Al)	Detector Area (cm ²)	Energy Deposition (MeV)	Count Range
1	82.5	0.008	0.050 - 1.000	1.0 - 10.0
2	232.5	0.051	0.050 - 1.000	1.0 - 10.0
3	457.5	0.051	0.050 - 1.000	1.0 - 10.0
4	886.5	1.000	0.050 - 1.000	1.0 - 10.0

Particles Measured					
Dome Number	Aluminum Shielding Thickness (gm/cm ²)	Detector Thickness (microns)	Lolet Elec. (MeV)	Lolet Prot. (MeV)	Hilet Prot. (MeV)
1	0.57	403	> 1.0	> 130	20-130
2	1.59	434	> 2.5	> 135	35-135
3	3.14	399	> 5.0	> 140	51-140
4	6.08	406	>10.0	> 155	75-155